United States Department of Agriculture | **Natural Resources Conservation Service** | **5 Radnor Corporate Center, Suite 200 Radnor, PA 19087-4585**

Subject: Geophysical Assistance

Date: 14 April 1999

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USDA – NRCS
6013 Lakeside Boulevard
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Purpose:

To assess the feasibility of using electromagnetic induction (EMI) and ground-penetrating radar (GPR) for estimating the depths to limestone bedrock within Floyd and Clark counties, Indiana.

Participants:

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Activities:

All field activities were completed during the period of 29 March through 2 April 1999.

Equipment:

The radar unit used was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.* The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 200 mHz antenna was used in this investigation. A 12-VDC battery powered the system. Morey (1974), Doolittle (1987), and Daniels and others (1988) have discussed the use and operation of GPR.

The electromagnetic induction meters used in this study were the EM38 and EM31, manufactured by Geonics Limited*. These meters are portable and require only one person to operate. No ground contact is required with these meters. These meters provide limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter operates at a frequency of 14,600 Hz and has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter operates at a frequency of 9,800 Hz and has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980a). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

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* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

Field Procedures:
Site selection was based upon soil and bedrock units. At each site, traverses lines were established to evaluate the performance of EMI and GPR. At each site, survey flags were inserted in the ground along a traverse line and served as observation points.

Measurements were taken at each observation points with an EM38 meter and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. With the EM31 meter, measurements are more easily obtained when the meter is held at hip-height than when it is placed on the ground surface. However, correlations between apparent conductivity and bedrock depths were improved when measurements were taken at the ground surface rather than at hip-height.

McNeill (1980a) found a 2.2 percent change in conductivity per degree (centigrade) change. All measurements were therefore standardized to an equivalent apparent conductivity at a reference temperature of 25° C (Sheets and Hendrickx, 1995).

Traverses were completed with GPR at two sites. Although, GPR provides a continuous profile of subsurface conditions, interpretations were restricted to the flagged observation points. At each observation point, the radar operator impressed a dashed, vertical line on the radar profile. This line identified an observation point on the radar record. Radar records were reviewed in the field.

At each observation point measurements of the depth to bedrock were obtained with a power auger or probe mounted on a vehicle. At each of these observation points, a brief profile description was prepared. These descriptions specified the depth and texture of the major soil horizons and the depth to bedrock or auger refusal. These data were used to confirm interpretations and develop predictive equations.

Background:

A soil survey report has been published for Clark and Floyd Counties, Indiana (Nickell, 1974). In each county, extensive areas were mapped as various phases of Crider soil. Crider is a member of the fine-silty, mixed, active, mesic Typic Paleudalfs family. Crider soil formed in loess and materials weathered from limestone bedrock. Loess ranges in thickness from 18 to 42 inches. The IIB horizon formed in fine textured materials (terra rosa) weathered from limestone bedrock. Depth to limestone bedrock ranged from 50 to 72 inches. In places, the limestone is capped or interbedded with strata of siltstone and/or shale.

In the process of updating the soil surveys of these counties, soil transects have revealed that bedrock depths can vary greatly over short distances within mapped areas of Crider soils. Soil scientists have noted that the determination of accurate bedrock depth measurements is difficult with conventional hand and power probes. Rock fragments, bedrock pinnacles and ledges, and solution cavities limit the effectiveness of these traditional soil-sampling tools for determining bedrock depths. The purpose of this study was to evaluate the potentials of ground-penetrating radar and electromagnetic induction to estimate depths to limestone bedrock and the taxonomic composition of soil map units in Floyd and Clark counties, Indiana.

Results:

Ground-penetrating radar:

The observation depth of GPR is dependent upon the presence, thickness, and electrical conductivity of the Bt horizon (argillic horizon) or layers of loamy and clayey materials within the substratum. In areas mapped as Crider soils in Floyd and Clark counties, radar signals are rapidly attenuated by loamy or clayey argillic horizons, layers of fine-textured *terra rosa* materials and residual materials weathered from shales or siltstones. Reflections from the limestone bedrock were only apparent on radar profiles where the bedrock outcrops or subcrops at shallow depths. In these areas, the argillic horizon was thin or not present, the radar signals were less attenuated, and observation depths were greater. Because of high clay contents and the rapid attenuation of radar signals, the use of GPR to determine the depths to limestone bedrock is inappropriate in Floyd and Clark counties.

Electromagnetic Induction

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980b). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction is not suitable for use in all soil investigations. Generally, the use of EMI has been most successful in areas where subsurface properties are reasonably homogeneous. This technique has been most effective in areas where the effects of one property (e.g., clay, water, or salt content) dominate over the other properties. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989). In Clark and Floyd counties, soils that have formed in loess and/or till over residuum weathered from limestone bedrock are more conductive than the underlying limestone bedrock. These soils have greater clay and moisture contents, and consequently higher apparent conductivity than the underlying limestone bedrock. Typically, areas that are shallower to bedrock have lower values of apparent conductivity than areas that are deeper to bedrock. Broad spatial trends and generalized groupings of bedrock depths can be inferred from EMI data.

Electromagnetic induction provides moderate resolution of subsurface features. With EM38 and EM31 meters, lateral resolution is purportedly equal to the intercoil spacing (3.3 and 12.7 feet, respectively). However, tests with the EM31 meter have revealed a footprint area of about 20 feet at the surface. As a consequence, this meter provides a depth-weighted measure of apparent conductivity for a comparatively large volume of soil (theoretically 9.8 to 19.7 feet deep with a diameter of about 20 feet at the surface). In Floyd and Clark counties, EMI provides too coarse a measurement to resolve the microtopogarphy of the bedrock surface especially small pinnacle, solution features, ledges, and rock fragments. However, measurements of bedrock depths obtained with a Giddings probe can be misleading. All to often, it is unclear weather the measured depth to auger refusal reflects the actual depth to the bedrock surface, a floater, or a minor solution feature. The contrast in the areas of measurement between the point of auger and the *area* of EMI observations were evident in this study. These differences weakened correlations.

Study Sites:

Site #1 - Crandall-Navilleton-Careyville silt loams, 12 to 22 percent slopes.

The site is located near Greenville in Floyd County. The site was in pasture and owned by Ken Ray. A 225 foot transect line was established perpendicular to the slope contours. Survey flags were inserted in the ground and served as observation points. At each of the 10 observation points, measurements were taken with the EM38 and EM31 meters. Table 1 lists the data from Site #1. At three observation points, bedrock was not encountered within the probed depth and was recorded as being greater than 14.9 feet. These three observation points were excluded from further data analysis.

Table 1
Basic Transect Data for Site #1

Observation	EM38H	EM38V	EM31H	EM31V	Bedrock Depth Feet
0	22.5	26.0	32.1	37.9	>14.9
25	25.8	27.5	32.4	31.8	>14.9
50	25.0	22.9	29.2	25.4	>14.9
75	14.5	11.9	19.4	18.0	18.7
100	10.4	8.6	15.3	21.1	16.3
125	21.4	14.1	19.9	14.4	1.4
150	17.4	9.9	13.9	9.5	1.1
175	20.8	7.6	14.5	11.3	1.1
200	19.9	7.3	15.3	10.8	1.0
225	26.4	15.6	19.9	12.8	1.2

Based on seven observation points, the depths to bedrock average 5.8 feet and ranged from 1.0 to 18.7 feet. Bedrock depths were highly variable with a standard deviation of 8.07 feet.

A comparison of soil probe and EM data collected at these observation points revealed both positive (with EM31 meter) and negative (with EM38 meter) relationships between the observed depths to bedrock and apparent conductivity. Relationships were weakened by variations in soil properties (e.g., texture, thickness, and depth of soil horizons; amount of coarse fragments; and moisture contents) and irregular bedrock surfaces. In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the hydraulic probe.

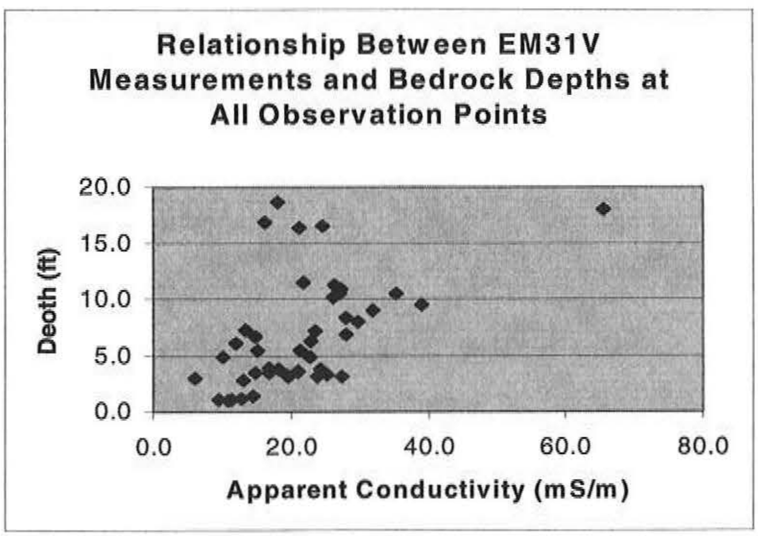
The correlations between depth to bedrock and apparent conductivity were -0.7985 and –0.0614 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. No explanation is possible at this time for these negative correlations. Correlation coefficients were 0.1643 and 0.8892 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Measurements of apparent conductivity obtained with the EM31 meter in the vertical dipole orientation had the highest correlation ($r = 0.8892$) with bedrock depth. Not surprising, the observation depth of the EM31 meter closely approximated the observed depths to bedrock (1.0 to 18.7 feet). Placed on the ground, the EM31 meter theoretically profiled to a depth of about 19.7 feet in vertical dipole orientation, respectively. These variations in the degree of correlation demonstrate the importance of selecting the most appropriate meter and coil orientation to obtain the desired observation depth and maximum resolution.

The observed depths to bedrock were compared with EMI data and used to develop a regression equation to predict depths to bedrock from values of apparent conductivity. Data collected with the EM31 meter in the vertical dipole orientation had the strongest correlation with the depth to bedrock and were used to develop a predictive regression equation:

$$D = -17.8934 + (1.695641 * EM31V) \qquad [1]$$

Where "D" is depth to bedrock (feet) and "EM31V" is the apparent conductivity (mS/m) measured with the EM31 meter in the vertical dipole orientation.

Equation [1] was used to estimate the depth to bedrock at each of the seven observations. At these observation points, the average difference in the depth to bedrock as measured by the hydraulic probe and predicted from EM measurements and equation [1] was 2.7 feet. Differences between observed and predicted depths ranged from –5.1 to 6.0 feet.



Site #2 - Navilleton- Crandall silt loams, 6 to 12 percent slopes.
The site is located near Greenville in Floyd County. A Mr. Haug owns the hayland. A 1125 foot transect line was established perpendicular to the slope contours. Survey flags were inserted in the ground at an interval of about 125 feet and served as observation points. At each of the 10 observation points, measurements were taken with the EM38 and EM31 meters. Table 2 lists the data from Site #2. At one observation points (#125), bedrock was not encountered within the probed depth. This observation point was excluded from further data analysis.

Based on seven observation points, the depth to bedrock average 10.7 feet and ranged from 8.0 to 18.0 feet. Bedrock depths were moderately variable with a standard deviation of 3.0 feet.

Table 2
Basic Transect Data for Site #2

Observation	EM38H	EM38V	EM31H	EM31V	Bedrock Depth Feet
0	24.1	35.2	51.5	65.5	18.0
250	11.6	17.5	30.2	39.0	9.5
375	15.3	20.0	27.7	27.9	8.3
500	19.1	26.0	29.9	29.6	8.0
625	19.3	21.6	26.0	27.1	10.5
750	21.9	26.3	36.3	31.8	9.0
875	17.7	15.5	30.5	35.2	10.5
1000	11.4	9.4	21.3	26.2	11.3
1125	8.3	10.0	23.3	27.2	10.9

A comparison of soil probe and EM data collected at these observation points revealed positive relationships between the observed depths to bedrock and apparent conductivity. Once again, relationships were weakened by variations in soil properties (e.g., texture, thickness, and depth of soil horizons; amount of coarse fragments; and moisture contents) and irregular bedrock surfaces. In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the hydraulic probe.

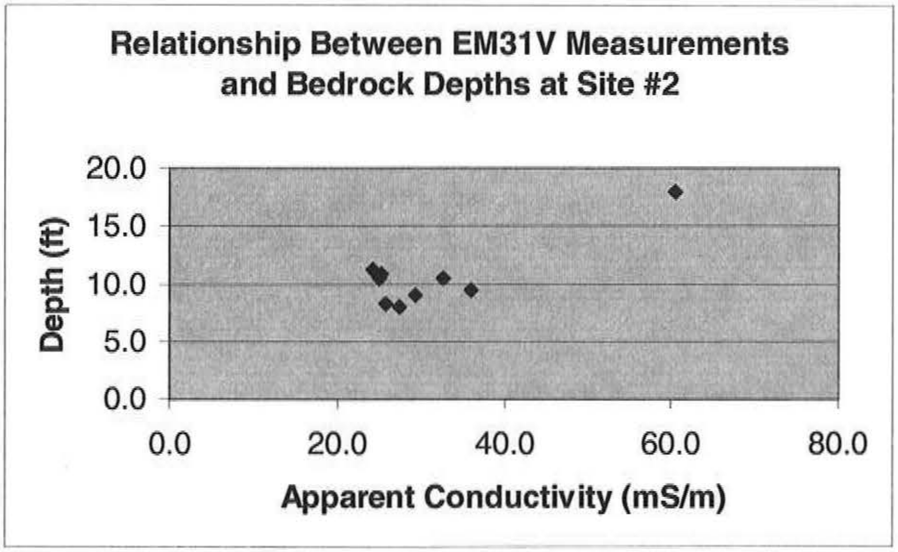
The correlations between depth to bedrock and apparent conductivity were 0.3399 and 0.4042 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. Correlation coefficients were 0.6876 and 0.8435 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Measurements of apparent conductivity obtained with the EM31 meter in the vertical dipole orientation had the highest correlation ($r = 0.8435$) with bedrock depth. The observation depth of the EM31 meter in the vertical dipole orientation most closely approximated the observed depths to bedrock (8.0 to 18.0 feet). Placed on the ground, the EM31 meter in the vertical dipole orientation theoretically profiles to depths of 0 to 19.7 feet.

The observed depths to bedrock were compared with EM data and used to develop a regression equation to predict depths to bedrock from values of apparent conductivity. Data collected with the EM31 meter in the vertical dipole orientation had the strongest correlation with the depth to bedrock and were used to develop a predictive regression equation:

$$D = 3.728415371 + (0.202283418 * EM31V) \qquad [2]$$

Where "D" is depth to bedrock (feet) and "EM31V" is the apparent conductivity (mS/m) measured with the EM31 meter in the vertical dipole orientation.

Equation [2] was used to estimate the depth to bedrock at each of the seven observation points. At these observation points, the average difference in the depth to bedrock as measured by the hydraulic probe and predicted from EM measurements and equation [2] was 1.4 feet. Differences between observed and predicted depths ranged from –2.1 to 2.2 feet.



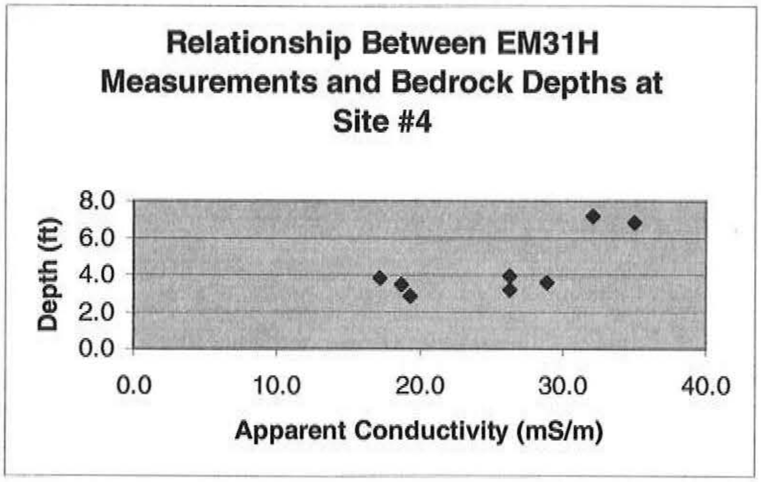
Site #4 - Crandall-Navilleton-Careyville silt loams, 12 to 22 percent slopes.
The site is located near Greenville in Floyd County. Tim Book owns the pasture. A 450 foot transect line was established perpendicular to the slope contours. Survey flags were inserted in the ground at intervals of 50 feet and served as observation points. At each of the 10 observation points, measurements were taken with the EM38 and EM31 meters. Table 3 lists the data from Site #4. At two observation points (#50 & #100), bedrock was not encountered with the probe. These observation points were excluded from further data analysis.

Based on eight observation points, the depth to bedrock averages 4.4 feet and ranged from 2.8 to 7.2 feet. Bedrock depths were variable with a standard deviation of about 1.7 feet.

Table 3
Basic Transect Data for Site #4

Observation	EM38H	EM38V	EM31H	EM31V	Bedrock Depth Feet
0	14.7	18.1	26.3	27.4	3.2
150	30.9	31.8	35.0	28.0	6.8
200	29.2	27.3	32.1	23.5	7.2
250	29.0	26.0	28.9	21.0	3.6
300	27.1	26.3	26.3	16.8	3.9
350	18.4	13.9	19.3	13.1	2.8
400	16.2	9.9	18.7	16.8	3.5
450	15.0	71.5	17.2	18.1	3.8

A comparison of soil probe and EM data collected at these observation points revealed positive relationships between the observed depths to bedrock and apparent conductivity. Once again, relationships were weakened by variations in soil properties (e.g., texture, thickness, and depth of soil horizons; amount of coarse fragments; and moisture contents) and irregular bedrock surfaces. In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the hydraulic probe.



The correlations between depth to bedrock and apparent conductivity were 0.1392 and 0.1603 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. Correlation coefficients were 0.7536 and 0.5699 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Measurements of apparent conductivity obtained with the EM31 meter in the horizontal dipole orientation had the highest correlation ($r = 0.7536$) with bedrock depth. The observation depth of the EM31 meter in the horizontal dipole orientation most closely approximated the observed depths to bedrock (2.8 to 7.2 feet). Placed on the ground, the EM31 meter in the horizontal dipole orientation theoretically profiles to depths of 0 to 9.8 feet.

The observed depths to bedrock were compared with EM data and used to develop a regression equation to predict depths to bedrock from values of apparent conductivity. Data collected with the EM31 meter in the horizontal dipole orientation had the strongest correlation with the depth to bedrock and were used to develop a predictive regression equation:

$$D = -0.54661243 + (0.19237602 * EM31V) \qquad [3]$$

Where "D" is depth to bedrock (feet) and "EM31V" is the apparent conductivity (mS/m) measured with the EM31 meter in the vertical dipole orientation.

Equation [3] was used to estimate the depth to bedrock at each of the seven observations. At these observation points, the average difference in the depth to bedrock as measured by the hydraulic probe and predicted from EM measurements and equation [3] was 0.92 feet. Differences between observed and predicted depths ranged from –1.5 to 1.5 feet.

Site #3 & 5 - Navilleton- Crandall silt loams, 6 to 12 percent slopes and Crandall-Navilleton-Careyville silt loams, 12 to 22 percent slopes

Two sites, both located on adjoining croplands near Greenville, in Floyd County were selected for investigations. Tim Book owns the cropland. At each site, a transect line was established perpendicular to the slope contours. Survey flags were inserted in the ground at intervals of about 50 feet and served as observation points. Soil depths were very deep at each site and augering was exceptionally difficult. A *kelly-bar* and an auger were lost at these sites. Data from these two sites were combined for analysis. Table 4 lists the data from sites #3 and #5.

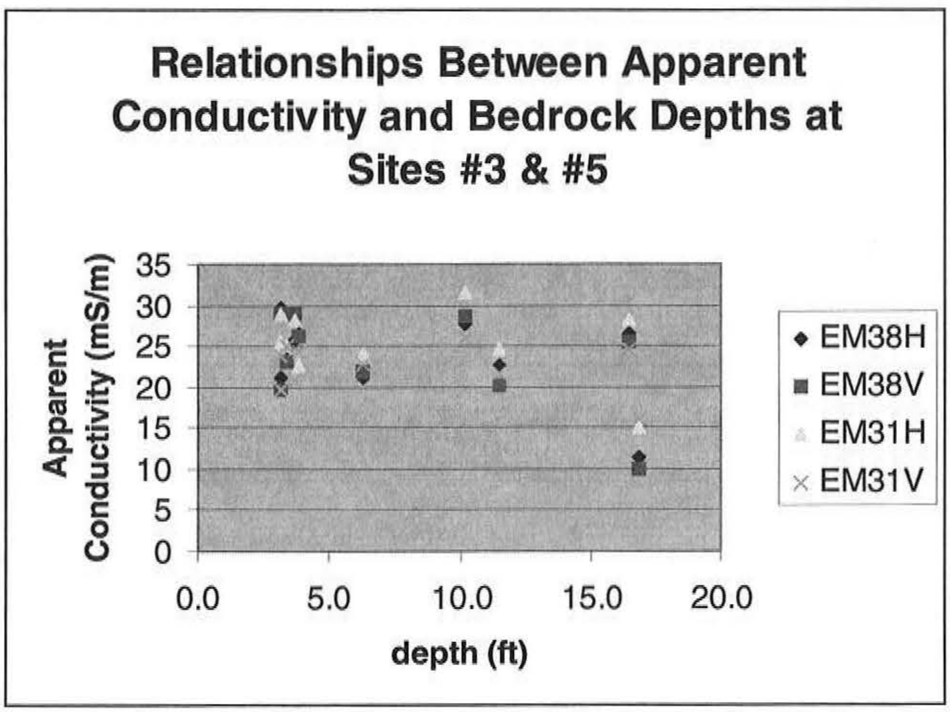
Based on ten observation points, the depth to bedrock averages 7.8 feet and ranged from 3.3 to 16.8 feet. Bedrock depths were highly variable with a standard deviation of about 5.5 feet.

Table 4
Basic Transect Data for Sites #3 and #5

Observation	EM38H	EM38V	EM31H	EM31V	Bedrock Depth Feet
1	21.1	19.7	25.4	23.7	3.2
2	22.6	20.2	24.5	21.7	11.5
3	26.5	25.4	28.1	24.5	16.5
8	11.5	9.9	15.0	16.1	16.8
1	29.7	28.9	28.9	19.6	3.2
3	27.7	28.6	31.6	26.1	10.2
4	21.2	21.8	24.0	22.8	6.3
5	25.8	28.9	28.3	20.9	3.7
9	26.4	26.3	22.6	24.2	3.8
10	24.7	23.1	25.1	25.1	3.3

A comparison of soil probe and EM data collected at these observation points revealed positive relationships between the observed depths to bedrock and apparent conductivity. Once again, relationships were weakened by variations in soil properties (e.g., texture, thickness, and depth of soil horizons; amount of coarse fragments; and moisture contents) and irregular bedrock surfaces. In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the hydraulic probe.

The correlations between depth to bedrock and apparent conductivity were 0.0051 and -0.4908 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. Correlation coefficients were -0.3226 and -0.2631 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Measurements of apparent conductivity obtained with the EM38 meter in the vertical dipole orientation had the highest correlation (r = -0.4901) with bedrock depth. No explanation is possible at this time to explan the negative relationships between apparent conductivity and bedrock depths. As two fields were combined in this analysis, differences in management (fertilizer applications) may have affected these measurements. Because of the low and negative correlations, a predictive equation was not developed for these sites.



Site #6 – Formerly mapped as Grayford soils
The site is located near Washington in Clark County. Tim Book owns the cropland. A transect line was established parallel with the slope contours. Survey flags were inserted in the ground at intervals of about 50 feet and served as observation points. Table 5 lists the data from Site #6.

Table 5
Basic Transect Data for Site #6

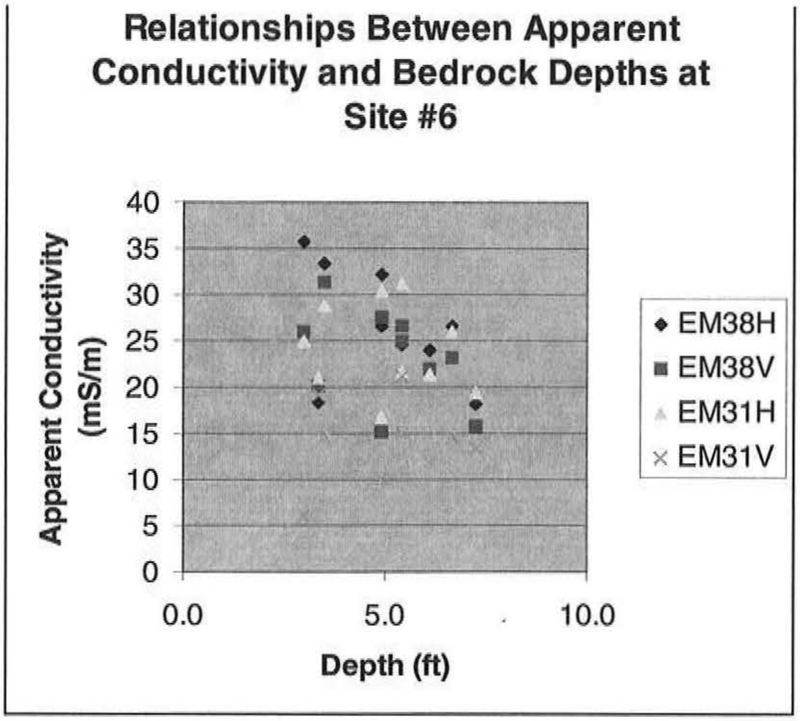
Observation	EM38H	EM38V	EM31H	EM31V	Bedrock Depth Feet
0	35.8	26.0	25.1	6.1	3.0
50	26.7	15.3	16.9	10.1	4.9
100	24.6	25.1	21.6	15.0	5.4
150	33.4	31.5	28.8	14.7	3.5
300	26.7	23.3	26.0	14.7	6.7
350	18.2	15.8	19.5	13.4	7.3
450	24.0	22.0	21.4	12.0	6.1
200	32.3	27.6	30.5	22.7	4.9
250	26.7	26.7	31.2	21.3	5.4
400	18.5	20.3	21.1	19.2	3.3

Based on ten observation points, the depth to bedrock averages 5.1 feet and ranged from 3.0 to 7.3 feet. Bedrock depths were relatively invariable with a standard deviation of about 1.4 feet.

A comparison of soil probe and EM data collected at these observation points revealed both negative and positive relationships between the observed depths to bedrock and apparent conductivity. Once again, relationships were weakened by variations in soil properties (e.g., texture, thickness, and depth of soil horizons; amount of coarse fragments; and moisture contents) and irregular bedrock surfaces. In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the hydraulic probe.

The correlations between depth to bedrock and apparent conductivity were -0.5028 and -0.4308 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. Correlation coefficients were -0.1952 and 0.0.971 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Negative correlations could reflect the affects of management. The presence of till, undoubtedly influenced these measurements. Measurements of apparent conductivity obtained with the EM38 meter in the horizontal dipole orientation had the highest correlation (r = -0.5028) with bedrock depth.

Because of the general weakness of relationships between apparent conductivity and bedrock depths , no predictive equations were developed for this site.



<u>Summary of all Sites</u>

A total of 44 soil borings were completed (to refusal) with a power probe. For these observations, the average depth to bedrock was 6.8 feet with a range of 1.0 to 18.7 feet. One half of the observations had depths to bedrock between 3.33 and 9.66 feet. Because of the observed range in bedrock depths, the EM31 meter in the vertical dipole orientation has the most appropriate observation depth and is the most suitable meter.

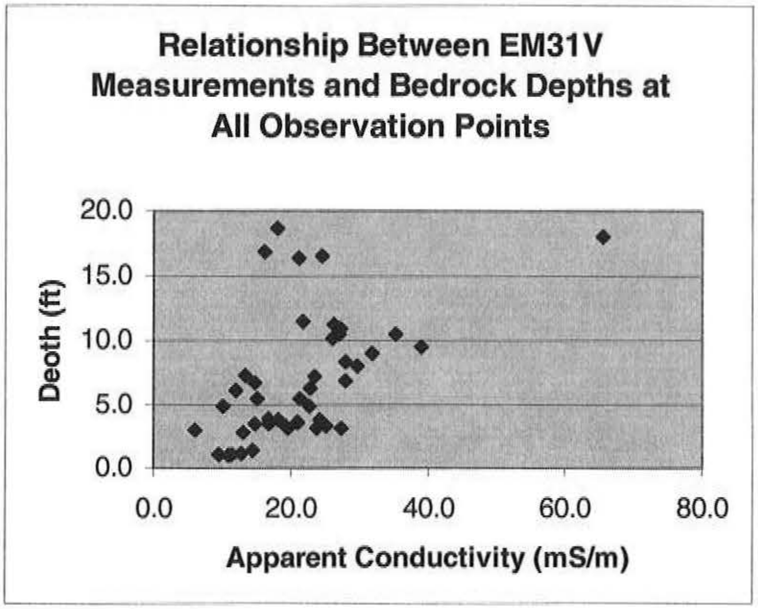
The correlations between depth to bedrock and apparent conductivity were -0.3618 and -0.0816 for the EM38 meter in the horizontal and vertical dipole orientation, respectively. Correlation coefficients were 0.2761 and 0.5254 for the EM31 meter in the horizontal and vertical dipole orientations, respectively. Measurements of apparent conductivity obtained with the EM38 meter in the vertical dipole orientation had the highest correlation ($r = 0.5254$) with bedrock depth.

The observed depths to bedrock were compared with EM data and used to develop a regression equation to predict depths to bedrock from values of apparent conductivity. Data collected with the EM31 meter in the vertical dipole orientation had the strongest correlation with the depth to bedrock and were used to develop a predictive regression equation:

$$D = 1.317106 + (0.513123 * EM31V) \qquad [5]$$

Where "D" is depth to bedrock (feet) and "EM31V" is the apparent conductivity (mS/m) measured with the EM31 meter in the vertical dipole orientation.

Equation [5] was used to estimate the depth to bedrock at each of the forty-four observation points. At these observation points, the average difference in the depth to bedrock as measured by the hydraulic probe and predicted from EM measurements and equation [5] was an unacceptable 6.5 feet. Differences between observed and predicted depths ranged from –8.1 to 16.9 feet. One half of the observations had differences between observed and predicted depths ranging from 4.5 and 8.37 feet.



Conclusions:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.
2. The observation depth of GPR is severely restricted by high rates of signal attenuation within the clayey argillic horizon and residuum. In many areas, observation depths will be less than 20 inches. Ground-penetrating radar is considered generally unsuitable for determining the depths to limestone bedrock in areas underlain by siltstones and shales of the Borden group.

3. The Silurian reef complex provides an unfavorable environment for EMI. At all sites, apparent conductivity was low and invariable. The range in recorded measurements was commonly less than the recognized range in observation errors (2 to 4 mS/m). As a consequence, the use of EMI was considered inappropriate and unreliable in areas of Marblehead and Castalia. Because of the high concentration of rock fragments, contrasts in electrical properties between the soil and the underlying bedrock were insignificant and immeasurable. Neither the EM38 nor the EM31 meter was able to detect differences in electromagnetic properties between the soil and bedrock. In addition, the large amounts of coarse fragments made ground-truth observations needed to correlate EMI measurements exceedingly difficult and time-consuming to obtain.

Can be used to help confirm where bedrock is relatively shallow or deep. This can help soil scientist confirm weather auger refusal was due to a "floater" or bedrock.
Interpretations of bedrock depths were generalized (areas of shallower or deeper depths to bedrock) from measurements of apparent conductivity. Broad spatial patterns can be discerned in the data (see Figure 1). However, a large number of backhoe observations are needed to confirm these interpretations and to establish predictive equations to convert apparent conductivity into measurements of bedrock depths.

It was my pleasure to work in Indiana and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

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